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A statistical analysis of weight and cost parameters of spacecraft with special reference to 'Aryabhata'

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Abstract. The available data on the weights of several NASA and ESRO spacecraft have been statistically analysed using the regression analysis technique and empirical relationships of the type $W_T = AW_x^{\beta}$ have been established, where W_T is the total weight of the spacecraft, W_x is the weight of one of its chosen subsystems and A and β are constants for the chosen subsystem. It is found that the weight data of *Aryabhata* show a fairly good fit with these empirical relationships. Further, using an established statistically derived relationship for NASA satellites, involving the cost of a spacecraft and its weight parameters, it is found that the cost of *Aryabhata* is much lower than that of other NASA satellites of comparable weight. The implications of these results are briefly discussed.

Keywords. Spacecraft weight; spacecraft cost.

1. Introduction

The weight and cost of a spacecraft are two important parameters on which careful control needs to be exercised. Whereas the shape and size of a spacecraft are essentially dictated by the shroud of the launch vehicle, the allowable total weight of spacecraft is limited by the capability of the launch vehicle. A few studies (Dondi 1971 and references therein; Clemens *et al* 1973) have indicated that the cost of a spacecraft can be expressed as a function of its weight and other technical parameters. Here we have analysed the available data (Dondi 1971) on the weight and cost of several spacecraft and compared the results with the corresponding data of *Aryabhata*. The following statistical analyses have been made.

(i) The available data on the weight parameters of different NASA and ESRO (European Space Research Organisation, now ESA, European Space Agency) satellites (Dondi 1971) have been used in regression analyses and the results are compared with the weight data of *Aryabhata*.
(ii) Based on an established empirical relationship between the cost of a spacecraft and its weight parameters, a comparison has been made between the cost of *Aryabhata* and the costs of several NASA satellites of comparable weight but having diverse complexities and mission goals.

A list of symbols appears at the end of the paper.

The present analysis shows clearly that as far as weight is concerned, *Aryabhata* compares fairly well with other satellites of its class; its cost is however lower than that of other satellites of comparable weight.

2. Analysis of weight data

The total weight of a spacecraft is the sum of the weights of its different subsystems, viz. power, telemetry and data handling, control and guidance, structure and on-board experiments. However, it is not known whether there exist relationships between the total weight of a satellite and the weights of its different subsystems. With a view to establishing such relationships, we analysed statistically the weight data of several NASA and ESRO satellites. It turns out that these can be related through expressions of the type

$$W_T = A W_x^{\beta}. \tag{1}$$

The weight data for a number of NASA and ESRO satellites (Dondi 1971) and for *Aryabhata* are shown in table 1. The weight range of spacecraft considered extends from about 40 to 470 kg. In order to examine the correlation between the total weight of a satellite and the weights of its different subsystems, the total spacecraft weight and the weights of the different subsystems for different satellites have been

Table 1. Weight break-down of satellites

(All weights are in kg)

Sl. No.	Satellite	W_S	W_{TD}	W_{PW}	W_{GC}	W_E	W_T
1	Ranger 6-9	120	40	114	27	47	356
2	Ranger 1-5	88	30	73·5	24	56	277
3	IMP A-C	19·5	6	18	1	16·5	61
4	IMP D-E	17	7·5	19	1	9.5	93
5	Mariner-R	60·5	38	46·5	24	21·5	198
6	Mariner-64	62	51	70·5	37	20·5	252
7	OGO A-E	182	71·5	81·5	49	86	470
8	RELAY	20·5	20·5	35	1·5	5·5	83
9	SYNCOM	9	14·5	6	4	0	38
10	SURVEYOR 1-7	133·5	24·5	45	38	12	356
11	OSO	70	19·5	23·5	28	113	254
12	ESRO-II	24·5	10	14	5	21·5	75
13	ESRO-I A	34	12·5	16	2·5	20	85
14	HEOS A-1	40	8·5	17	8·5	27	101
15	ESRO-I-B	34	12·5	16	2·5	20	85
16	HEOS A-2	41	9	18·5	11	25·5	105
17	TD	184	33	35·5	86·5	116	455
18	ESRO IV	22	11·5	20	8·5	32	94
19	*Aryabhata*	148·95	47·16	58·78	50·45	53·11	358·45

Note.—For some of the satellites W_T also includes the weight of the propulsion system which has not been listed in this table

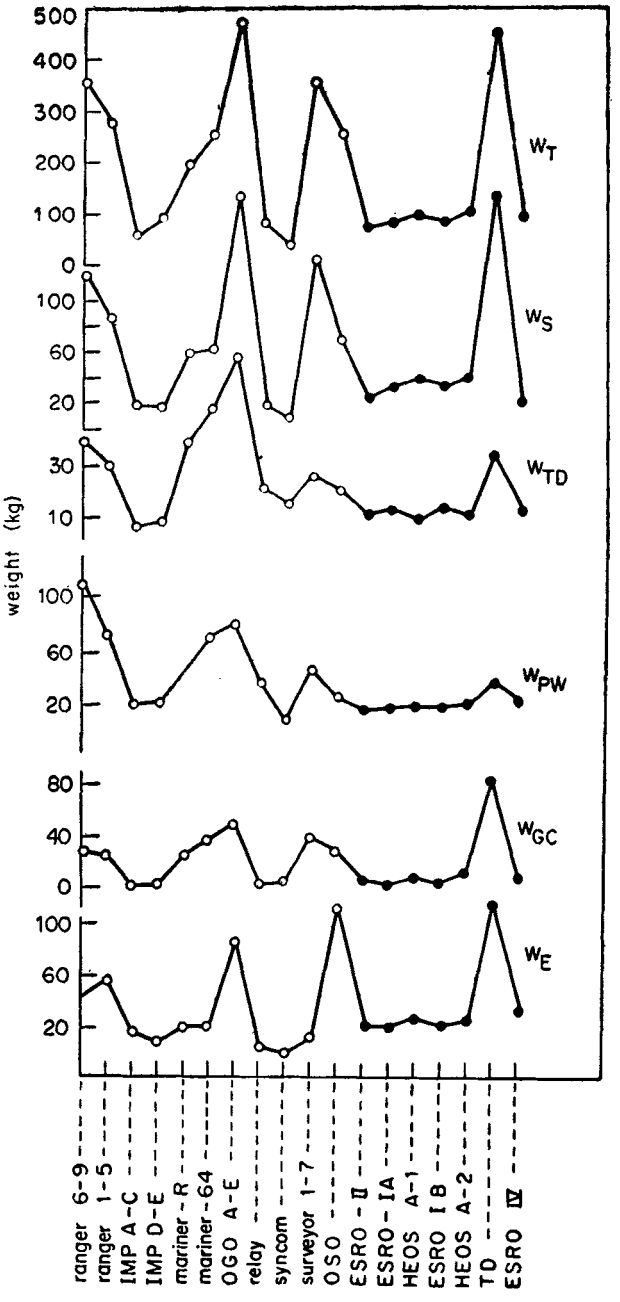

Figure 1. The weight data (as listed in table 1) for the 18 satellites are plotted in this diagram to show the correlation between W_T and weights of different sub-systems. The names of the different satellites are shown on the x-axis.

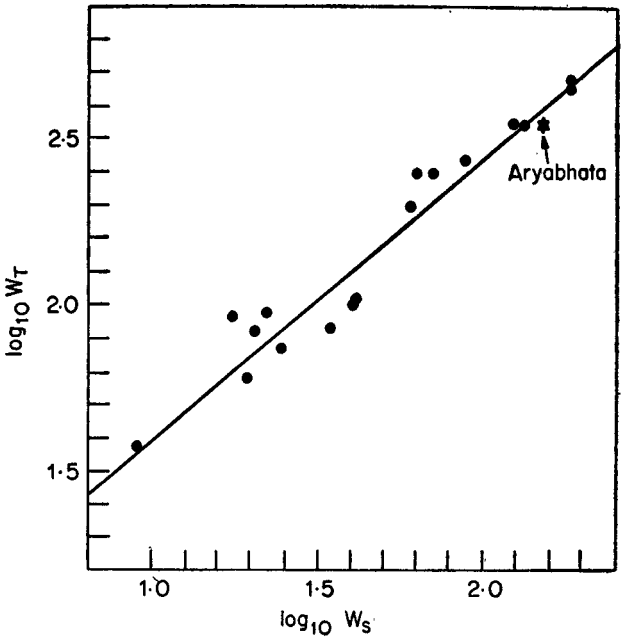

Figure 2. Scatter plot of log W_T against log W_S. The data point corresponding to *Aryabhata* is shown in the diagram by a star.

Table 2. Correlation co-efficients between different variables

Variables	Correlation coefficients
log W_T, log W_S	0·96 ± 0·02
log W_T, log W_{TD}	0·81 ± 0·08
log W_T, log W_{PW}	0·85 ± 0·06
log W_T, log W_E	0·63 ± 0·15
log W_T, log W_{GC}	0·80 ± 0·06

Table 3. Coefficient A and exponent β in equation (1)

Subsystem	A	β
Structure	5·69	0·85
Telemetry and data handling	12.2	0·86
Power	8.3	0·86
Experiments	27·1	0·53
Guidance and control	49·1	0·49

plotted in figure 1. It can be seen from this figure that the weights of different subsystems show good correlation with the total weight of the spacecraft.

Figures 2–6 show the scatter plots of log W_T against log W_x (where x stands for different subsystems). In table 2, the correlation coefficients corresponding to these scatter plots are given. Note that all the correlation coefficients are high and

significant. The coefficient A and the exponent β for different subsystems in the empirical relationship (1) obtained by the method of least squares analysis, are displayed in table 3.

These empirical relationships can provide useful guidelines for estimating the weights of different subsystems of any satellite during the initial system design phase. However, it should be noted that these empirical relationships are only

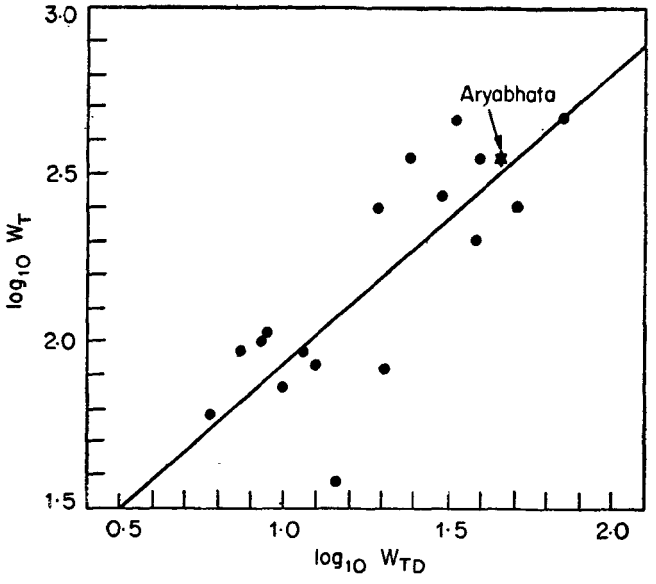

Figure 3. Scatter plot of log W_T against log W_{TD}. The data point corresponding to *Aryabhata* is shown in the diagram by a star.

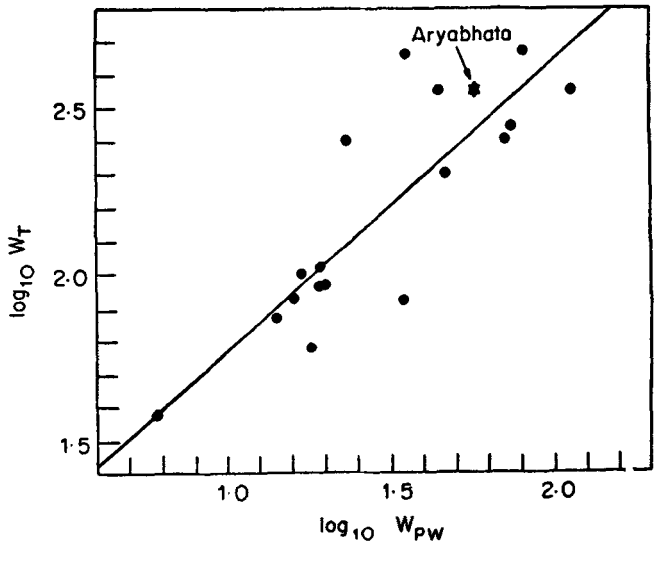

Figure 4. Scatter plot of log W_T against log W_{PW}. The data point corresponding to *Aryabhata* is shown in the diagram by a star.

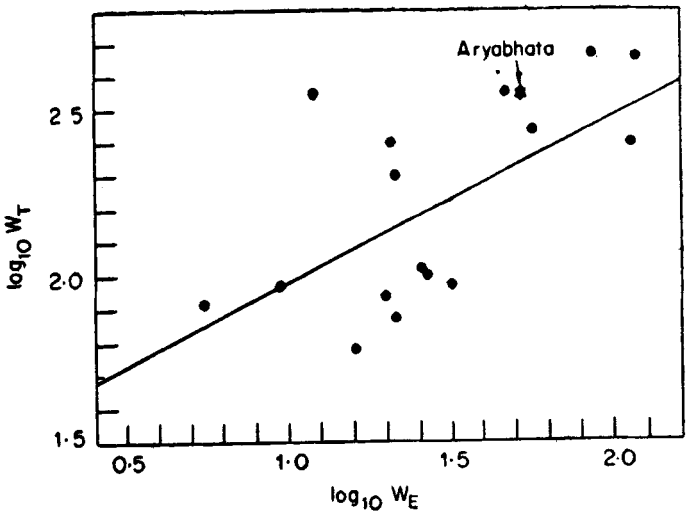

Figure 5. Scatter plot of log W_T against log W_E. The data point corresponding to *Aryabhata* is shown in the diagram by a star.

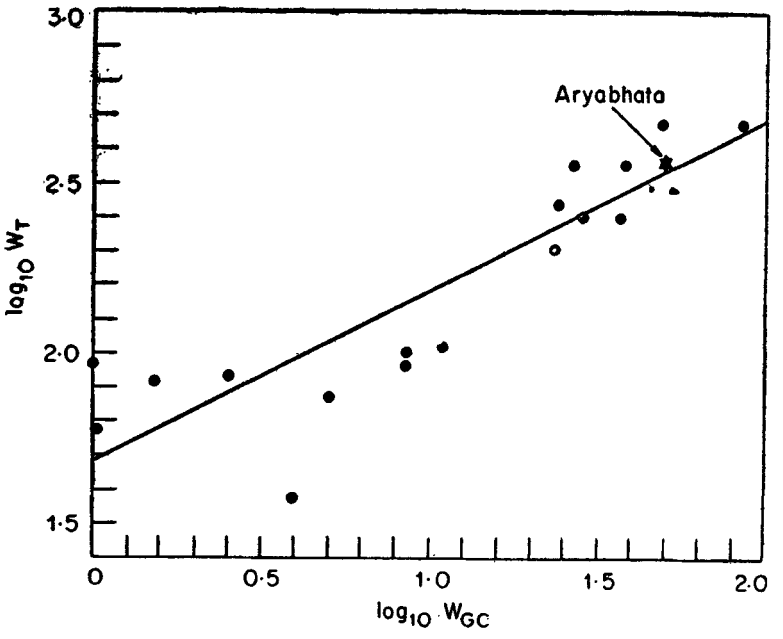

Figure 6. Scatter plot of log W_T against log W_{GC}. The data point corresponding to *Aryabhata* is shown in the diagram by a star.

approximate; the calculated subsystem weights from these relationships agree with the actual weights within about $\pm 20\%$. In particular, it may be noted that since there is a large scatter (correlation coefficient $= +0{\cdot}6$) in the plot of log W_T vs log W_E, the corresponding empirical relationship has relatively less accuracy.

It is important to note that weight data for different subsystems of *Aryabhata* show a fairly good fit with these empirical relationships, as may be seen from the scatter plots (figures 2–6).

It is important to note here that in deriving these relationships we have used the weight data of different NASA/ESRO satellites of the late sixties. It seems quite possible that with advancement in satellite technology, these weight relationships might change.* It would be therefore important to also study such weight relationships for the satellites of 1970's which represent a higher level of technology than that for the earlier period. In this context it is significant to note that these weight relationships when applied to the recent satellites of ISRO, viz. APPLE and INSAT, give consistently underestimated values for the total in-orbit weights for these satellites.

3. Relationship between weight and cost of spacecraft

Some studies (Dondi 1971 and references therein; Clemens *et al* 1973) have been made to establish empirical relationships between the cost of a spacecraft and its different weight parameters. For example, the total cost C_{SG} of a spacecraft including the cost of experiments and cost of the relative ground support (i.e. launch vehicle and mission support) is given by the Goddard formula

$$C_{SG} = 25{\cdot}95\,(W_{TD}/W_T)^{1{\cdot}237} \cdot (NW_T)^{1{\cdot}08} \cdot (\text{DTC. TAR})^{0{\cdot}035} \text{ Rs. in lakhs} \quad (2)$$

where the cost is in lakhs of rupees, and we have taken \$ 1=Rs. 7·50. Note that in the above formula, the cost is strongly dependent upon (i) the complexity factor for the satellite (W_{TD}/W_T) i.e., the ratio of the weight of the telemetry and data handling subsystem to the total weight of the satellite and (ii) NW_T — i.e., the total weight of the manufactured satellites with the package of on-board experiments (prototype and flight models). The last factor in equation (2) which involves the product of the 'degree of time compression' and 'technical advance required' does not contribute significantly to the total cost.

For comparison with *Aryabhata*, we use the following values for the different parameters:

$N = 3$ (prototype and two flight models); DTC = 4; and TAR = 3.

Using the empirical relationship between W_T and W_{TD} as established in § 2, equation (2) can now be simplified to:

$$C_{SG} = 2{\cdot}54\ W_T^{1{\cdot}28} \text{ Rs. in lakhs.} \quad (3)$$

We shall call (3) the modified Goddard formula. This equation has been plotted in figure 7 along with the cost data (Dondi 1971) of some NASA satellites (3 models for each) and of *Aryabhata*. The total cost of *Aryabhata* has been derived as follows. The total cost of the three models of *Aryabhata* is Rs. 3·5 crores. Adding to this Rs. 1·5 crores for the approximate cost for the subsystems (spin system, chemical battery, solar panels and tape recorders) supplied by the USSR Academy of Sciences,

*The author is thankful to the referee for this suggestion.

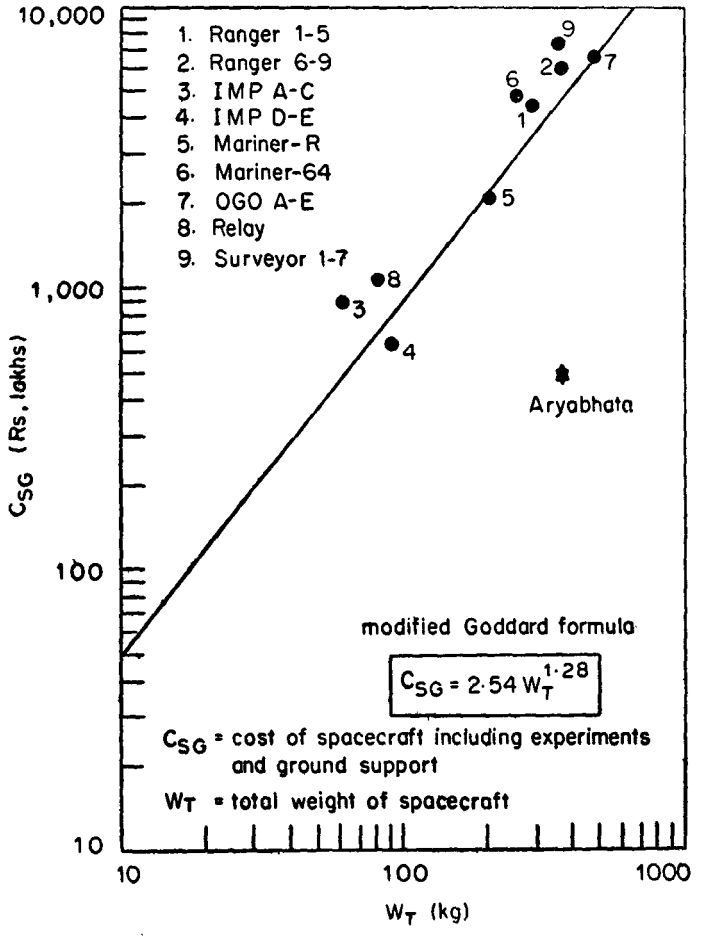

Figure 7. The cost of spacecraft as a function of its total weight as given by the modified Goddard formula (equation (3)). The cost data of several NASA satellites and of *Aryabhata* are also shown.

which is considered a reasonable estimate in view of the international cost of these items, the total cost of *Aryabhata* works out to be Rs. 5 crores. However, this cost cannot be directly compared with the costs of NASA satellites (shown in figure 7) which include the cost of the relative ground support also. From the cost data of NASA satellite projects (Dondi 1971) it is found that, on an average, the cost of a spacecraft including on-board experiments works out to be about 60% of the total cost, while the remaining 40% accounts for the relative ground support. Thus, based on this result and using (3), the cost of a spacecraft including on-board experiments, for a satellite of the same weight as that of *Aryabhata* (i.e. 350 kg), works out to be about Rs. 27 crores, which is about five times higher than the cost of *Aryabhata*.

4. Discussion of results

The result regarding the cost aspect of *Aryabhata* is quite significant and therefore, this warrants a more detailed study by taking into consideration the data regarding

the cost, weight as well as other technical factors related to the complexity of a satellite. Although the complexity factor W_{TD}/W_T is hidden in the modified Goddard formula (equation (3)) it does not seem to be applicable to *Aryabhata*. This might mean that probably the factor W_{TD}/W_T may not be a true representation of the complexity of *Aryabhata*. Alternatively, other technical parameters related to spacecraft capability such as available power, type of stabilisation and control system, number of experiments, telemetry bit rate etc. of a spacecraft should also be considered for the analysis of cost estimation. In this connection it is important to note that from the consideration of the available power*, *Aryabhata* does not compare well with the NASA satellites of similar weight. Whereas *Aryabhata*'s available power is 46 W, the average power level for NASA satellites of 400 kg weight is about 200 W. Perhaps this could be one of the possible reasons for the lower cost of *Aryabhata*. However, this should be considered tentative until it is verified by rigorous analysis. In this context it would be more meaningful to study *Aryabhata*'s weight versus capability in relation to other satellites.

In addition, there could also be some nontechnical reasons for the lower cost of *Aryabhata*, and *prima facie* the following two causes appear to be more significant.

(i) The lower overhead charges and salary structure in India as compared to those in USA.
(ii) The practice of sub-contracting normally followed in NASA satellite programmes might involve larger costs compared to in-house activities as was the case with *Aryabhata*.

5. Conclusions

The main conclusions that can be drawn from the present analysis are summarised as follows.

(i) The statistical analysis of the weight data of several NASA and ESRO satellites does indicate empirical relationships between the total weight of a spacecraft and the weight of any of its subsystems. These empirical relationships can provide useful guidelines during the initial system design phase of a spacecraft.
(ii) The existing Goddard formula for estimating the cost of a spacecraft has been simplified so that the cost is given as a function of only the total weight of the spacecraft.
(iii) Based on the empirical relationships mentioned in (i) and (ii) above, a comparison of the weight and cost parameters of *Aryabhata* shows that whereas the subsystem weight parameters of *Aryabhata* are in good agreement with those of other satellites of comparable weight (i.e. about 350 kg), the cost of *Aryabhata* is much lower than the cost of other satellites of similar weight.

In view of the ongoing and future satellite programmes of ISRO, it would be worthwhile to compare the costs of several Indian satellites with those of NASA and ESRO satellites, along with other relevant parameters. It might turn out from this analysis that such direct comparisons are not justified. A somewhat

*The author is thankful to the referee for pointing out this.

analogous situation also probably exists (Dondi 1971) in relation to the cost comparison between US and European satellites, giving rise to what is known as the 'Atlantic factor' which is the ratio between the developmental costs in aerospace industries in US and Europe. In such a case, it would be necessary to evolve some independent and reliable cost-estimation relationships for the Indian satellites alone.

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List of symbols and abbreviations

A	constant for a given subsystem of a satellite
C_{SG}	total cost of a spacecraft including the cost of on-board experiments and the relative ground support (i.e. launch vehicle and mission support)
DTC	degree of time-compression in the project: 1 (minimum); 2 (small); 3 (medium); 4 (large)
N	total number of satellites fabricated, including prototypes
TAR	technical advance required in the state-of-the-art at the inception of the programme: 1 (small); 2 (medium); 3 (large)
W_E	weight of on-board experiments in a satellite (kg)
W_{GC}	weight of guidance and control system of a satellite (kg)
W_{PW}	weight of electrical power system of a satellite (kg)
W_S	weight of structure, including the weight of cabling and thermal control system of a satellite (kg)
W_T	total weight of a satellite (kg)
W_{TD}	weight of telemetry and data handling system including the weight of house-keeping subsystem of a satellite (kg)
W_x	weight of any subsystem of a satellite (kg)
β	constant for a given subsystem of a satellite
One lakh	10^5
One crore	10^7

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